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(54) ELECTRICAL NETDORKS INCLUDING SEMICONDUCTOR ELEMENTS

(71) We, MICROWAVE ASSOCIATES, INC., a corporation organized under the laws of the Commonwealth of Massachusetts, United States of America, of South Avenue, Burlington, Massachusetts, United States of America,
 do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to electrical networks including semiconductor elements.

According to the present invention there is provided an electrical network for operation in a given band of electric wave frequencies, comprising at least one semiconductor element which when suitably biased exhibits negative resistance in the given operating frequency band, biasing means and mounting means for said element having inductance of magnitude such that the range of natural resonant frequencies of said element in the biasing and mounting means is different from said given operating frequency band, said semiconductor element being less effective as a negative resistance device in said range of natural resonant frequencies than in said given operating frequency band, means to bias said element to exhibit said negative resistance in said given operating frequency band, and translating means coupled to said element for extracting electric wave energy in said given operating frequency band from said element.

The present invention may be used in the field of microwave generation and amplification of higher power. Embodiments of the invention employ in combination one or a multiplicity of elementary devices which may be treated as two-terminal impedance elements which exhibit negative-resistance properties and are capable of individually generating high frequency oscillations over particular ranges of frequencies when suitably biased by a battery or other source of power.

One suitable element is the Read avalanche diode or other PN junction diode biased into reverse avalanche discharge. This is a semiconductor P-N junction device first described by Read[1]. Alternative forms have been described by DeLoach *et al.* [2]. Another suitable semiconductor device is the Gunn diode[3] which consists of a wafer of gallium arsenide biased with a dc source. Gallium arsenide devices operating in the "LSA" mode are also suiable, as described by Copeland.[4] Transistor type structures may also be used if these can be arranged in an elementary form which provides a negative-resistance at high frequency at two terminals. Still other forms might include PNPN type semi-conductor diodes, tunnel diodes, and the like. This invention is not primarily concerned with the internal structure of these elementary devices but rather with the circuits and structures in which they are placed. The invention applies to the application of any type of such oscillating or negative-resistance semiconductor device, including those not mentioned above

Previous techniques for combining multiple individual elements include several basic approaches. There is for example the technique of placing several small elements lose together in a shunt or parallel combination across a high voltage gap in a single resonator or cavity. Parallel operation in this way

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[1] W. T. Read, "A proposed high frequency negative-resistance diode", Bell Systems Tech. Journal, PP 401—466, March 1968.

[2] R. L. Johnston, B.C. DeLoach, Jr., B.G. Cohen, "A Silicon Diode Microwave Oscillator", Bell Systems Tech. Journal, PP 316—372, February 1965.

[3] J. B. Gunn, "Microwave Oscillations of Current in III—V Semiconductors", Solid State Comm. Vol. 1, PP 87—91, Sept. 1963.

[4] J.A. Copeland, "L.S.A. Oscillator Diode Theory", Journal of Applied Physics, pp. 3096—3101, July, 1967.

[*Price 25p*]

is limited to relatively few elements in a given resonator because they must be very closely spaced and the impedance level decreases in inverse proportion to the number used. Very low impedances cause high resistive losses in the resonator and present severe problems in coupling. A corollary approach has been to place several elements in a series stack in a single resonator. The series combination, however, presents serious problems in extracting the heat generated by the elements in the center of the stack. Heat must flow outward through the others, severely limiting the total power dissipation.

Another prior technique involves the use of many single microwave resonators with separated input and/or output transmission lines. Fukui[3] has described such a technique for combining multiple separate oscillator circuits through the use of hybrid transmission line power combiners. When many elements are to be combined, the complexity and cost of such techniques becomes prohibitive.

Techniques for combining-negative resistance diodes were described by Hines in U.S. Patents #3,051,908 and #3,231,831. The first of these, while providing for broadband amplification, is limited in output power capability because the technique used to couple the transmission line and the diode elements requires that each element be activated by the full line voltage. Using the present invention, on the other hand, a substantial improvement may be achieved over the prior approaches in that very large numbers of semiconductor elements may be used in a single structure to provide high power operation equivalent to the sum of the power available from each element.

A basic problem in combining many active negative-resistance elements for high power oscillation or amplification in a given frequency band is that of "moding", in which spurious or undesired modes of oscillation will occur at frequencies different from those in the desired band. At high frequencies, complex networks containing many electrical impedance elements generally have many "normal modes" of possible transient oscillation. When negative-resistance elements are included in such a network, continuous or erratic oscillations can occur in such modes if their resonant frequencies lie in a frequency range where the negative-resistance of the elements is effective. Such oscillations are called "spurious modes" when they involve undesired frequencies or internal electrical field patterns differing from the ones desired. The presence of spurious modes of oscillation will diminish the usefulness of a circuit or system for most applications.

It is a feature of this invention that spurious modes may be eliminated by appropriate network design criteria to be described.

In the accompanying drawings Figure 1 shows qualitatively-sketched graph illustrating the behaviour of the conductance of some types of negative-resistance semiconductor device elements. This graph shows the type of variation with frequency to be expected. All of the devices presumed to show negative conductance (or resistance) in a band including the frequency f_o desired. All of the devices also shown this negative conductance to be decreasing in magnitude and becoming positive at high frequencies (e.g.: f_s) far above the desired band. Some devices also show reduced or vanishing negative conductance effects at lower frequencies, will separated from the band in which the device is intended to be used.

In order to avoid spurious oscillations, the networks described herein are designed so that all of the normal resonant modes except the one desired occur at higher or lower bands of frequency than the desired operating frequency band. Thus, if the spurious modes have frequencies in the general vicinity of f_s or higher, no oscillations can occur in such modes because the active elements have only positive or very small negative conductance at such frequencies. It is thus also possible to avoid oscillation at frequencies where there is a small residual negative conductance near the cross-over such as f'_s on Figure 1, because circuit losses can be sufficient to prevent oscillation in such marginal cases.

It has also been found that the presence of strong oscillations at one frequency can cause the suppression of undesired modes of oscillation which might occur at other frequencies in other modes, even if the devices exhibit strong negative resistance effects at these other frequencies when not oscillating strongly. All negative devices are nonlinear such that when strongly oscillating at one frequency, the alternating voltage periodically drives the device into positive-resistance portions of its current-voltage characteristic curve. In fact, when a negative resistance device is driven by a strong alternating voltage of such a magnitude as to extract the maximum useful power at the driving frequency, it is found that the time-average value of its negative conductance has vanished. With slightly higher alternating voltage applied the time-average conductance is positive. Under such conditions, oscillations at other frequencies may see no effective negative resistance and cannot start.

Thus, it is not always necessary to remove the other resonant modes into frequency bands where no negative resistance is found. Substantial frequency separation between the desired and undesired modes is necessary, how-

[3] H. Fukui, "A Multiple Silicon-Avalanche Diode Oscillator" International Electron Devices Meeting, October 26—28, 1966, Digest of Paper, p52.

ever, for this method of suppression to be effective. Mode suppression by strong signals is a most effective techniques for high power amplifiers where an input signal insures that oscillation occurs at the proper frequency in the proper mode.

This invention may be used in the field of microwave generators and amplifiers of power and may be applied in particular to provide circuits and mounting structures for employing a plurality of semiconductor elements to generate or amplify microwave energy. Embodiments of this invention may be constructed which provide useful circuits and mounting structures for multiple semiconductor elements so that they will act in unison to provide a single high frequency signal either coherently in a combined oscillation, or in synchronism under rf drive to provide a faithfully amplified replica of an input signal, and with a power output capability equivalent to the sum of the output capabilities of the many semiconductor elements used.

Also, the invention may be used to provide a mounting structure for a plurality of semiconductor elements which can conduct away the excess heat energy produced by a multiplicity of elementary devices.

Furthermore, the invention may be used to provide an electrical circuit for the multiple devices which allows a wider tuning range in the case of an oscillator, or increased frequency bandwidth in the case of an amplifier than may be obtained with prior techniques.

For a better understanding of the invention, and to show how the same may be carried into effect, reference will now be made, by way of example, to the accompanying drawings in which:

Fig. 1 shows the above-referenced graph of conductance variation vs. frequency;

Fig. 2 illustrates an equivalent circuit of a first network embodying the present invention;

Fig. 3 graphically represents an example of the undesired frequencies at the higher end of the spectrum relative to the desired frequencies;

Fig. 4 illustrates an equivalent circuit of a second network embodying the present invention;

Fig. 5 illustrates an equivalent circuit of a third network, which relates to a variation of the embodiment of Figure 4;

Fig. 6 graphically represents an example of undesired frequencies at the lower end of the spectrum relative to the desired frequencies;

Fig. 7 illustrates the equivalent circuit of a fourth network embodying the present invention wherein coupling is obtained inductively to a transmission line or waveguide;

Fig. 8 illustrates the equivalent circuit of a fifth network, which relates to a variation of the embodiment of Fig. 7;

Fig. 9 schematically illustrates a device comprising a multiplicity of semiconductor elements mounted in a laminated block structure;

Fig. 10 schematically illustrates the device of Fig. 9 mounted in a wall of a section of rectangular waveguide;

Fig. 11 schematically illustrates a cavity resonator of cylindrical shape with its inner wall formed as a cylindrical stack of laminae using a construction similar to that of the Fig. 9 device;

Fig. 12 is a cross-section on line 12—12 of Fig. 11;

Fig. 13 schematically illustrates the device shown in Figure 9 in combination with a transmission line;

Fig. 14 schematically illustrates part of a microwave device having the equivalent circuit shown in Figure 5;

Fig. 15 is a vertical section showing part of the device of Fig. 14 in the bottom wall of a cylindrical cavity;

Fig. 16 is an isometric view of part of a microwave embodiment of the equivalent of Figure 8; and

Figs. 17 and 18 illustrate the construction shown in Figure 9 as applied to a coaxial transmission line.

Figure 2 shows an equivalent circuit of one network embodying this invention, shown herein lumped-element circuit form for purposes of explanation. A microwave-structure having this equivalent circuit is shown in Figs. 11 and 12. The semiconductor elements (hereinafter sometimes called "active elements") are shown in Figure 2 as semiconductor diodes 4. These are biased through inductors 3(L_d), by-passed to ground through capacitors 5, in parallel by a bias battery 6 connected across the by-pass capacitors. The inductance L_d represent the inductance of the biasing and mounting means of each diode 4.

A larger inductor 1, of value L_T is in a primary resonator subcircuit which is resonated in a band including the desired frequency f_o by the series capacitor 7(C_T). The resonance frequency may be calculated by the formula

$$f_o = \frac{1}{2\pi} \sqrt{L_T C_T}$$

Each of the smaller inductors has a mutual inductance M_1 with the larger inductor 1. A small inductance M_2 may also be present between adjacent smaller inductors 3.

An output line 7′ is coupled through output inductor 2 and mutual inductance M_3 to the primary resonator L_T, C_T. The diodes 4 each have a capacitance C_d and there will be a resonant frequency f_s computed by the for-

mula $f_s = \frac{1}{2\pi}\sqrt{L_dC_d}$. This in the natural resonant frequency of the diode in its biasing and mounting means.

A complex network of this kind containing a large number of resonant loops coupled together will normally have as many resonant or "normal" modes as there are resonant loops. Because of interaction among the loops, however, these normal modes are at somewhat different frequencies than would be found in the individual loops if they were not coupled together. Any one such mode will normally involve circulating currents flowing in all of the loops simultaneously. The various distinct modes may be distinguished by different frequencies and by different phase difference relationships of the currents among the various loops.

For purposes of illustration and without inteding to limit the scope of the invention it is assumed that four diodes are used in four small loops as shown in Fig. 2. (Numbers of diodes much larger than four may be utilized; hundreds or even thousands of semiconductor elements are contemplated). Suppose that the outer (primary resonator) loop containing inductor 1 and capacitor 7 has a resonant frequency f_o and that the individual diode loops each have a nominal or "natural" resonant frequency f_s which is higher, perhaps on the order of 2 f_o. A complete analysis of such a network show resonant modes at frequencies approximately as shown in Fig. 3. This shows the line spectrum of such modes. The mode near f_o will be perturbed to a slightly lower frequency f'_o. In addition there will be pertubed to a slightly lower freqency f'_o. In addition there will be four modes in the band of frequencies near f_s, in general falling between the limits

$$\frac{f_s}{\sqrt{1+\left(\frac{2M_2}{L_d}\right)}} \leq f_m \leq \frac{f_s}{\sqrt{1-\left(\frac{2M_2}{L_d}\right)}}$$

In general, the mutual inductance M_2 will be much smaller than the self-inductance L_d so that the band containing the four upper modes will lie in a narrow range about f_s. The lower-freqeuncy mode f'_o near f_o is the desired frequency mode.

The negative conductance properties of the diodes 4 are such as to be substantially ineffective at frequencies near f_s so that oscillations are not possible in these modes. However, if the diodes have a substantially negative resistance effect in the band of lower frequencies including f_o, frequencies in this band including f'_o) can be coupled into the primary resonator loop of inductor 1 so that the network may oscillate or amplify using this low-frequency mode only. It is significant that all of the diodes can be coupled equally into this mode so that each can provide an equal share to the total power output of the network in the lower frequency band.

This principle of mode separation is a major feature of the invention. The network just described accomplishes the desired aim of combining many negative-resistance elements into a single network with a single output, combining the power capabilities of all of the elements. The network also avoids the hazards of oscillation in undesired resonant modes of the network. This has been accomplished through a network in which all modes but the one desired are in a band of frequencies where the active elements are substantially ineffective as negative-resistances or power generators.

Figure 4 illustrates an alternative circuit arrangement which can provide an equivalent degree of mode separation. In this network, the primary resonator including inductor 11(L_T) and capacitor 10(C_T) is resonant at or near the desired frequency f_o. An output line 9 is inductively coupled to the inductor 11. Again, a multiplicity of active semiconductor elements, here represented as diodes 15, are coupled, capacitively through a multiplicity of small capacitors 12(C_c), instead of inductively as in Figure 2. The many loops containing the diodes are intended to be similar to one another and to be resonant at or near a frequency where the active elements 15 are substantially ineffective as power generators or negative resistance elements. By-pass capacitors 14 complete each loop for a.c., and bias voltage from a battery 16 is applied across each of these capacitors. In this class of network, it may be more appropriate if each of the local diode resonant loops has a natural resonant frequency lower than f_o. Such a circuit is suitable for the Read or avalanche diode element, which is not effective as a negative conductance at the lowest frequencies (See Fig. 1.) The mode spectrum for such a circuit is illustrated in Fig. 6. The resistors 18 shown in each local diode loop may be intentionally inserted, or they may represent the inherent lossiness of the inductors 13. Such resistors may be of additional help in suppressing undesired modes of resonance.

Figure 5 shows another method of coupling negative-resistance elements into the circuit of Fig. 4. As in Fig. 4, many such diodes (now in pairs 15, 15) may be coupled into a single primary resonator (L_TC_T). In this case, two diodes biased in series through a small inductor 19 are shown. This inductor will desirably have a very small value of inductance (L_d) and in the limit may represent only the unavoidable inductance of a direct electrical connection (i.e.: the diode mounting and biasing means). In this case, the local diode loop resonant frequency is that of the

two diode capacitances in series with the inductor 19. This will be most suitable for local resonant frequencies (f_s) much higher than the desired frequency (f_o), giving a spectrum as shown in Fig. 3. The coupling current path from the common terminal 17 through any coupling capacitor 12 divides between the two diodes which are connected each in series with that capacitor.

The basic circuits of Figs. 2, 4 and 5 are suitable as described for use as high frequency oscillators. Such circuits can also be used as negative-resistance amplifiers, by techniques now well known in the field. To do so, a signal generated elsewhere may be injected through a ferrite circulator (not shown) into the output line 7′ (Fig. 2) or 9 (Fig. 4). This signal wave can be caused to be reflected from the network along the line with a power greater than that applied. This amplified reflected wave can be separated externally in a known manner by the use of the ferrite circulator. If the mutual coupling inductance (M_3 in Figures 2 and 4) is made sufficiently large, self oscillation of such a network can usually be prevented, and amplification will, nevertheless, be obtainable.

In accordance with known principles oscillators of the types herein described may be 'injection locked' by a technique similar to that described above the amplification. Such oscillations may be caused to assume the identical frequency of an injected signal wave, giving an output power greater than the power injected.

It may be noted that the circuits of Figures 2, 4 and 5 might also include two or more diodes in series where only one is shown in each local diode loop. Similarly each semiconductor element in each of these circuits might consist of two or more small diodes in shunt in place of the one shown.

Another set of alternative arrangements of the invention involves coupling a multiplicity of active elements, using same principles, into waveguides or transmission lines instead of into resonators. Fig. 7 shows an example of an inductively coupled approach for multiple diodes in a transmission line or waveguide. Such a transmission line or waveguide may be represented schematically as having distributed inductance L_L per unit length along the path 22 and distributed capacitance shown as many shunt capacitors 29(C_L). Each small loop contains an inductor 20 (L_d) and an active (e.g. diode) element 21 with capacitance C_d resonant at some frequency substantially different from the desired operating frequency where the negative conductance of the element is largely ineffective. A by-pass capacitor 28 completes each loop, and bias voltage is applied to the active elements in parallel. A mutual inductance M_1 exists between each small diode loop and the distributed inductance 22(L_L) of the transmission medium. A small mutual inductance M_2 may also exist between adjacent small diode loops. As in the resonator case, a number of resonant modes or transmission modes involving the mutually coupled small loops with be present. Again, the frequency range for these will lie in a narrow band of frequencies as indicated by the relation

$$\frac{f_s}{\sqrt{1+\left(\frac{2M_2}{L_d}\right)}} \leq f_m \leq \frac{f_s}{\sqrt{1-\left(\frac{2M_2}{L_d},\right)}}$$

where f_s is the nominal resonant frequency of each small loop if it were uncoupled. As before, substantially no oscillations will occur in such modes if the negative conductance of the semiconductor elements 21 is substantially ineffective in this band of frequencies.

However, at all frequencies, a wave traveling on the transmission line 22 will be coupled to each diode loop through mutual inductances M_1 and, in the band of frequencies where negative conductance effects occur, it will be found that this coupling will add power to a traveling wave on the line in exactly the converse way in which positive resistance in such loops would cause a loss of power from the traveling wave.

Figure 8 shows a similar type of transmission line in which the multiple active elements 26 are coupled to the transmission line through small capacitors 25(C_C) instead of through mutual inductance. Here the series diode pair arrangement of Fig. 5 is shown but the local circuit arrangement near the diodes as shown in Fig. 4 is equally applicable. The principle is similar to that in Fig. 7. Again, spurious modes can be eliminated by the same principles of frequency and power will be added to a traveling electro-magnetic wave as it passes through the line 22.

In the two alternative arrangements, shown in Fig. 7 and Fig. 8 very large numbers of diodes can be used. If the coupling mutual inductances or capcitances are small, then a very high power wave may propagate on the line, yet each diode element will be excited by a voltage or current from the wave which can be predetermined at a value for optimum power transfer from the diode to the line without exceeding its voltage or current capability. This value is determined by the value of the coupling mutual inductance M_1 or coupling capacitance C_C, and other parameters of the network.

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The discussion up to this point has been concerned with schematic diagrams using lumped-element networks of the kind which are common for radio frequencies up to the lower parts of the U.H.F. bands. These have been useful in explaining the behaviour of

these new circuits. However, many applications of this invention are at much higher frequencies, extending from the UHF bands through the microwave bands up to 10,000 MHz and beyond. In devices for such frequencies, distributed-constants types of networks are commonly used. Equivalence between lumped element and distributed element networks is a common feature of microwave technology such that distributed networks are often described in terms of approximate lumped-element equivalent circuits. Some distributed network element configurations of these devices will now be shown which more closely resemble, in a physical sense, the networks used in practice in the microwave region.

Referring to Fig. 9, a laminated block structure is shown consisting of several layers of metal 30 with thin layers of dielectric 31 separating and insulating them one from another. Step cut-outs 34 are formed in each metal layer confronting each other in pairs as shown with a row of active solid-state elements 32 in each of the resulting slots between adjacent layers 30.1 and 30.2; the elements may be semi-conductor diodes soldered or bonded in place via their respective electrodes. A bias source 33 applies bias voltage between the alternate and intervening metal layers 30.1 and 30.2 to activate the active devices, which might be Read avalanche diodes, Gunn diodes, tunnel diodes, or any other type of active negative-resistance element. Such a block structure including elements and layers of metal and dielectric can include a large number of active elements. Twentyfive are shown in this figure for illustration, but much larger numbers are possible. To radiate away excess heat, the alternate layers 30.1 may extend beyond the intervening layers 30.2 at the lower end of Fig. 9, for example.

A block 35 of this sort includes by-pass capacitance in the dielectric spacing layers 31 corresponding to the capacitors 5 in Fig. 2 and 28 in Fig. 7. There will be a local inductance associated with each active device in a current path including the element itself and the metal surface down the sides and across the bottom of the slot in which the element is installed. This corresponds to the inductors 3 (L_d) in Figure 2 or inductors 20(L_d) in Figure 7.

Such a block 35 can be used as an integral portion of a resonant cavity or a microwave transmission line, being placed for example so that high frequency currents of the cavity or waveguide will flow across the slotted surface of the block in a direction perpendicular to the slots. Associated with such current flow there will be a magnetic field in the slots. The inductance associated with this magnetic field occupies some of the same volume as that due to circulating currents through each semiconductor element 32, thus forming a mutual inductance between the element loops and the waveguide or cavity in which the block is installed.

Fig. 10 shows a block 35 of this type presenting its slotted surface as one of the narrow side walls of a section of waveguide line 36. This principle may be extended by placing such blocks on one or both sides repeatedly or continuously along the axial length of the waveguide for an extended distance. An input wave can be introduced at one end and an output wave taken from the other end of the line 36.

Fig. 11 shows a cavity resonator 41 of cylindrical shape with its cylindrical wall 38 formed as a cylindrical stack using construction similar to the rectangular stack of Fig. 9. Here, the active face of the cylindrical stack is the inner slotted cylindrical surface, with the active semiconductor element 32 arranged in annular slots around the inner circumference. This corresponds quite closely to, and forms a microwave embodiment of, the circuit of Fig. 2, using forty elements instead of four. Here a tuning screw 40 is shown in the cavity 41. This cavity 41 is the equivalent of the resonator L_TC_T of Figure 2, with the tuning screw 40 providing the adjustment of capacitor 7(C_T). Fig. 12 illustrates the placement of the active elements 32 with respect to the cavity 41. Output can be taken via the output terminal 42.

Fig. 13 shows how a block 35 containing many elements 32 according to Fig. 9 may be used as another wall of a waveguide or transmission line, here on one of the wide faces 38 where surface current flow is substantially parallel to the direction of power flow. The upper and lower conductors 37, 38 shown in Fig. 13 may also be the separate conductors of a "slab" or other type transmission line.

Fig. 14 shows part of a microwave device having the equivalent circuit shown in Fig. 5, illustrating the active elements and their biasing and mounting means. The block 35′ is similar in construction to that of Fig. 9, except that two elements are placed in series in each slot formed by the cut-outs 34. A small metallic probe, "flag" or antenna 46 is attached at the mid-point between each pair of diodes 32, 32 extending a short distance above the slotted surface, as shown. These probes will be sufficient to provide the capacitance C_c, corresponding to capacitors 12 of Fig. 5 or 25 in Fig. 8.

Fig. 15 shows a section of a cylindrical cavity 48 with such a block 35′ installed in the bottom wall. The probes 46 couple lightly, in a capacitive sense, to the resonator. The tuning screw 40′ is similar to the screw 40 in Fig. 11, and the output terminal 42′ is like 42 in Fig. 11.

Fig. 16 shows a similar block 35′ in a side wall of a rectangular waveguide 49, present-

ing its slotted surface to the interior to provide part of a microwave embodiment of the equivalent circuit of Figure 8. Here the probes 46 extend a short distance toward the opposite wide side wall of the waveguide 49 and form small capacitive coupling to a traveling wave propagating in the waveguide.

The transmission line amplifier circuits of Figs. 7, 8, 13, and 16 may have a serious drawback, as illustrated, in that amplification will occur for waves traveling in either direction along the line. If high gain is attempted in an unbroken length of line, oscillations can occur unless the lines are accurately matched in impedance to the load and source. Reflected waves can make multiple transits, with gain in both directions, causing oscillation. To avoid such oscillations, ferrite materials may be inserted into the lines using the types of ferrite which give greater power absorption for one direction of propagation than for the other. Many such techniques are well known in the art. An alternative approach is to use numerous short sections of transmission line, each with relatively low amplification. Ferrite isolators can then be inserted between sections to perform the same function. Many types of isolators are now well known in the art, and none is illustrated here.

Figs. 17 and 18 show a coaxial line having an inner conductor 44, and an outer cylindrical conductor incorporating a cylindrical stack 38 similar to that of Figs 11 and 12 in its outer wall.

WHAT WE CLAIM IS:—

1. An electrical network for operation in a given band of electric wave frequencies, comprising at least one semiconductor element which when suitably biased exhibits negative resistance in the given operating frequency band, biasing means and mounting means for said element having inductance of magnitude such that the range of natural resonant frequencies of said element in the biasing and mounting means is different from said given operating frequency band, said semiconductor element being less effective as a negative resistance device in said range of natural resonant frequencies than in said given operating frequency band, means to bias said element to exhibit said negative resistance in said given operating frequency band, and translating means coupled to said element for extracting electric wave energy in said given operating frequency band from said element.

2. A network according to claim 1, wherein the said element is a semiconductor diode.

3. A network according to claim 2, in which said diode has a capacitance, and said inductance of the biasing and mounting means has a magnitude such that said inductance resonates with said capacitance at a frequency in said range of natural resonant frequencies.

4. A network according to claim 1, in which said element exhibits positive conductance in said range of natural resonant frequencies.

5. A network according to claim 1, in which said element exhibits negative conductance in said range of a natural resonant frequencies, the magnitude of the negative conductance in said range being substantially smaller than the negative conductance exhibited in said given operating frequency band.

6. A network according to any preceding claim, comprising a multiplicity of such semiconductor elements, biasing means and mounting means for each of said elements having inductance of magnitude such that the range of natural resonant frequencies of each of said elements in the biasing and mounting means is different from said given operating frequency band, the semiconductor elements being less effective as negative resistance devices in said range of natural resonant frequencies than in said given operating frequency band, means to bias said elements to exhibit said negative resistance in said given operating frequency band, and translating means coupled to all of said elements for extracting electric wave energy in said given operating frequency band from said elements.

7. A network according to claim 6, in which said translating means are a subcircuit including means to resonate the subcircuit at a frequency in said given operating frequency band, the network further comprising means for reactively coupling each of said elements to said subcircuit.

8. A network according to claim 7, in which said subcircuit comprises inductance and capacitance means and said elements are each inductively coupled to the inductance means.

9. A network according to claim 7, in which said subcircuit comprises inductance and capacitance means, each of said elements being coupled in series with respective capacitive means in parallel with said subcircuit.

10. A network according to claim 2, or according to claim 6 when read as appendant to claim 2, in which the or each diode is connected in a circuit loop in series with said inductance of its biasing and mounting means and a *d.c.* — isolating capacitor, the means to bias the or each diode comprising conductor means arranged to apply bias voltage across said isolating capacitor.

11. A network according to claim 6, in which said biasing and mounting means comprise first and second electrically-conductive layers having a dielectric layer between them and respective members extending beyond said dielectric layer separated from each other to form a channel having a bottom wall and two lateral walls, and an open side opposite the bottom wall, said elements being mounted in said channel between said members and each of said elements having two electrodes at least one of which is in direct electrical contact

with one of said members, the means to bias said elements being connected between said conductive layers, the capacitance of said conductive layers and the intervening dielectric layer and the inductance of the mounting means for said elements including said lateral and bottom walls of said channel serving to establish said range of natural resonant frequencies.

12. A network comprising a plurality of subassemblies each according to claim 11 having the first conductive layer of each subassembly confronting but dielectrically separated from the second conductive layer of the next subassembly, the channels of all the subassemblies being parallel to each other with their open sides confronting a common plane, the means to bias the elements being connected at one said to all of the first conductive layers in parallel and at another side to all of the second conductive layers in parallel.

13. A network according to claim 11, in which said translating means comprise a section of transmission line, said members being effectively coupled to said transmission line.

14. A network according to claim 11, in which the second electrode of each of said elements is spaced from the second of said members, and an electrical conductor is coupled to the second of said members and extends out of said channel, being connected at an intermediate point to said second electrode.

15. A network according to claim 11, comprising at least one pair of said elements arranged in series between said members, one electrode of one of said pair being in direct electrical contact with one of said members, one electrode of the second of said pair being in direct electrical contact with the other of said members, and the remaining electrodes of the elements of said pair being electrically conductively connected together.

16. A network according to claim 15, including an electrical conductor connected to said remaining electrodes and extending out of said channel through said open side thereof.

17. A network according to claim 16, including fielding confining means bonding a space for microwave electromagnetic wave energy, said field-confining means comprising an envelope of electrically-conductive material, said envelope having an aperture and said members being located effectively in said aperture with said open side of said channel confronting said space and said conductor extending into said space.

18. A network according to claim 17, in which said field-confining means are in the configuration of a rectangular waveguide and said channel is in an aperture located in a wide wall thereof, and said conductor extends parallel to the narrow walls of the waveguide.

19. A network according to claim 17, in which said field-confining means is in the configuration of a cylindrical cavity and said channel is located in an aperture in an end wall thereof, and said conductor extends substantially parallel to the cylinder-axis of said cavity.

20. A network according to claim 11, in which said translating means comprise field-confining means bounding a space for microwave electromagnetic wave energy, said field-confining means comprising an envelope being formed with an aperture and said members being effectively in said aperture with said open side of said channel confronting said space.

21. A network according to claim 20, in which said envelope comprises a cavity resonator.

22. A network according to claim 20, in which said envelope comprises a section of waveguide.

23. A network according to claim 20, including means to extract microwave energy from said space.

24. A network according to claim 20, including means to introduce microwave energy into said space and means to extract microwave energy from said space.

25. A network according to claim 20, in which said space is cylindrical and said channel is annular with its open side substantially concentric with the axis of said space.

26. A network according to claim 20, in which said field-confining means is in the shape of a rectangular waveguide, and said channel is in a side wall thereof and extends in the direction of the longitudinal axis thereof.

27. A network according to claim 20, in which said field-confining means is in the shape of a rectangular waveguide, and said channel is in a side wall thereof and extends in a direction transverse to the longitudinal axis thereof.

28. An electrical network for operation in a given band of electric wave frequencies, sbstantially as herein described with reference to any of Figures 2, 4, 5, 7, 8 and 10, or with reference to Figures 11 and 12, or with reference to any one of Figures 13, 14, 15, 16, 17 and 18, of the accompanying drawings.

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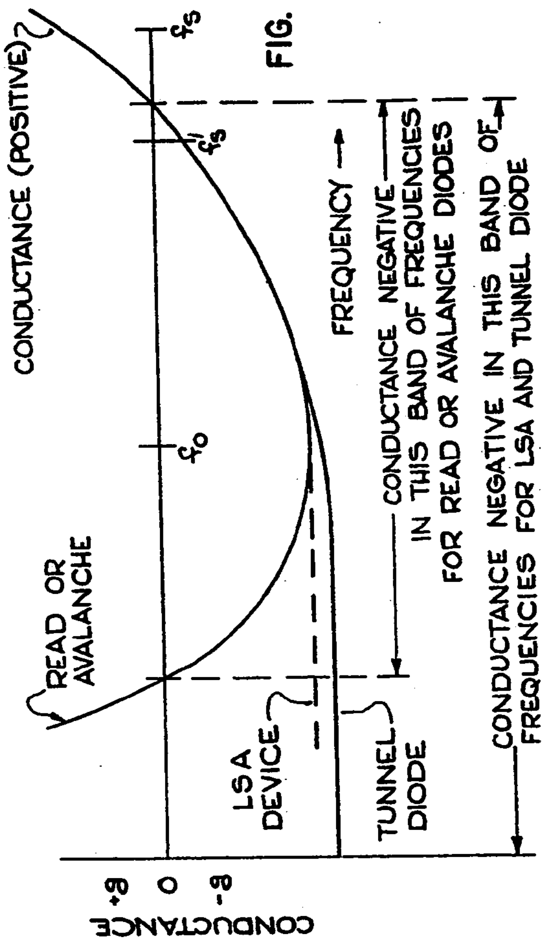

CONDUCTANCE (POSITIVE)
READ OR AVALANCHE
LSA DEVICE
TUNNEL DIODE
FREQUENCY →
CONDUCTANCE NEGATIVE IN THIS BAND OF FREQUENCIES FOR READ OR AVALANCHE DIODES
CONDUCTANCE NEGATIVE IN THIS BAND OF FREQUENCIES FOR LSA AND TUNNEL DIODE
CONDUCTANCE
g+
0
g-
fs
f's
fo

FIG. 1

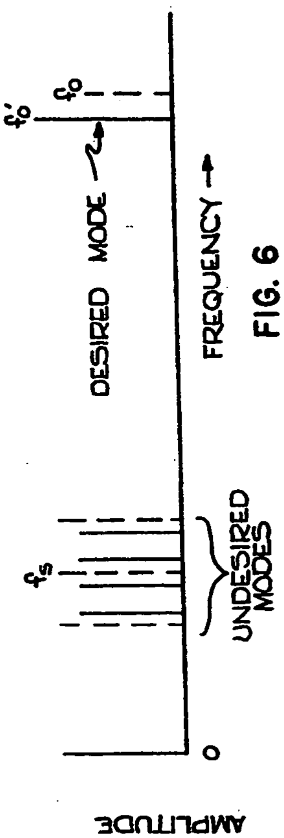

AMPLITUDE
0
FREQUENCY →
DESIRED MODE
UNDESIRED MODES
fs
fo
f'o

FIG. 6

1240188 COMPLETE SPECIFICATION

9 SHEETS *This drawing is a reproduction of the Original on a reduced scale*

Sheet 2

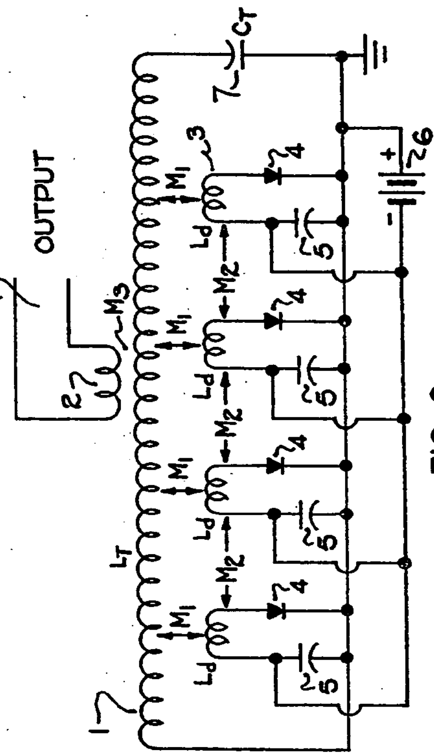


FIG. 2

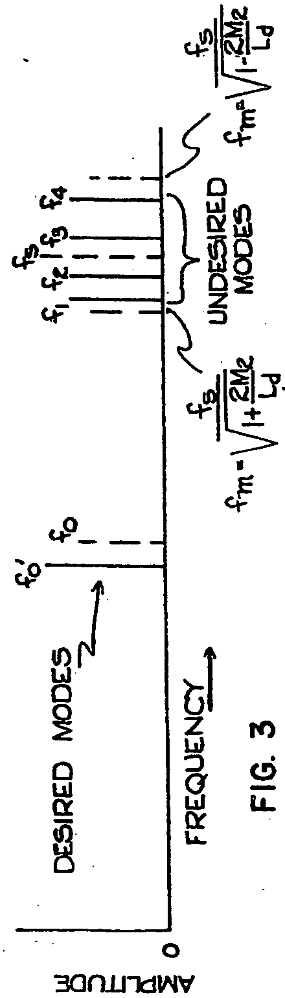


FIG. 3

1240188 COMPLETE SPECIFICATION

9 SHEETS *This drawing is a reproduction of the Original on a reduced scale*

Sheet 3

FIG. 4

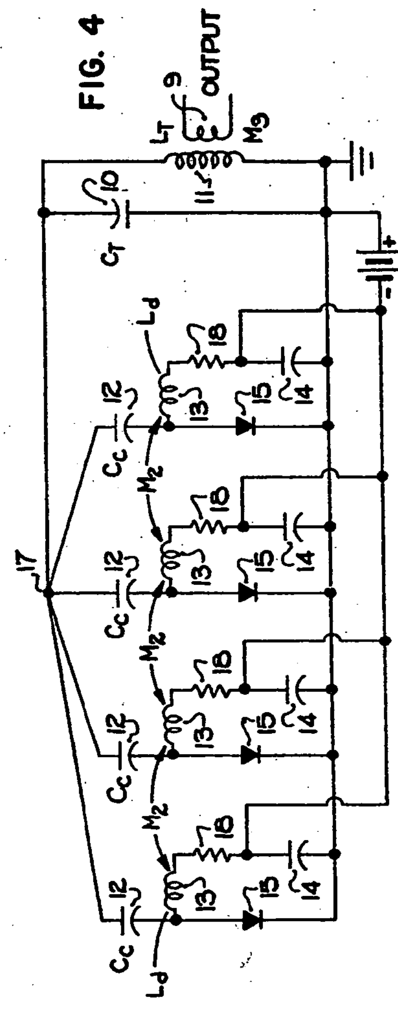
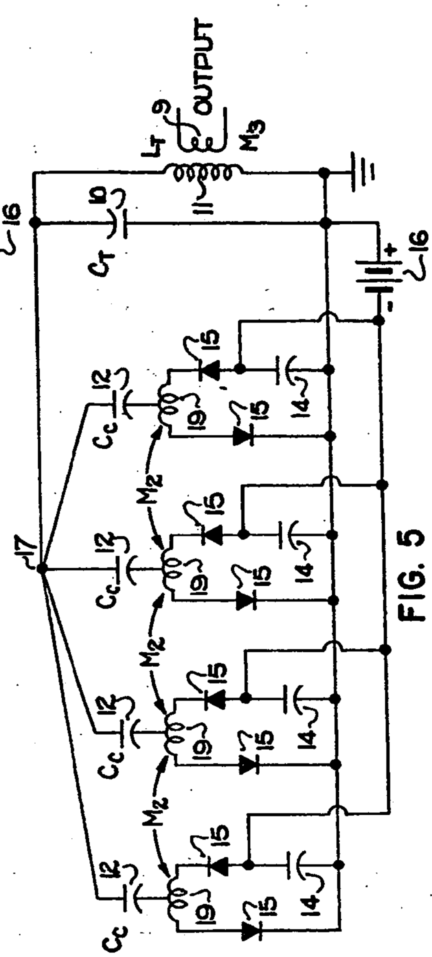


FIG. 5



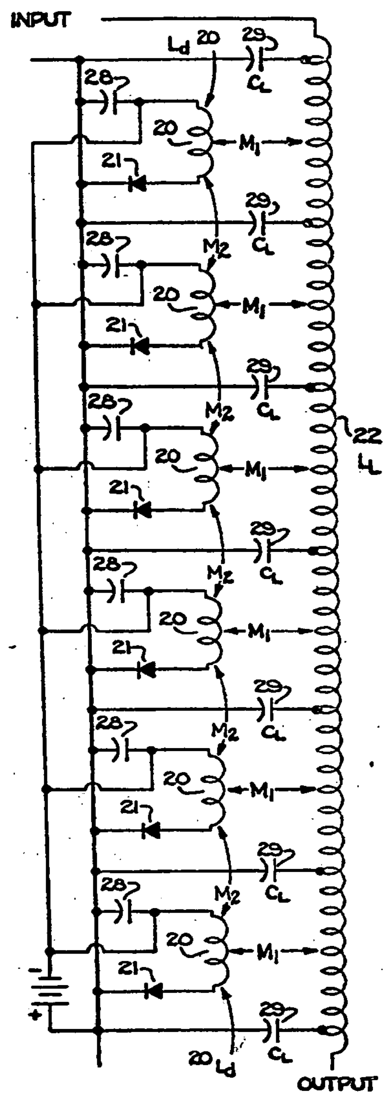

INPUT
Ld
20
29
CL
28
21
M1
M2
22
LL
20
OUTPUT

FIG. 7

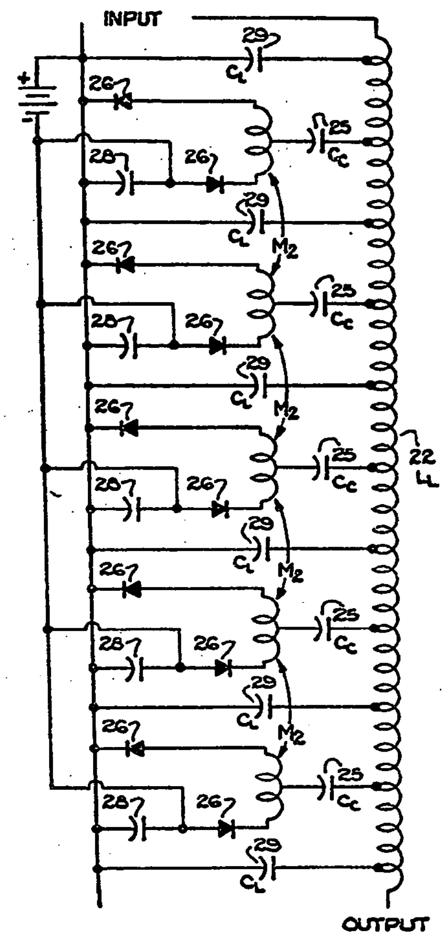

INPUT
29
CL
26
25
Cc
28
M2
22
LL
OUTPUT

FIG. 8

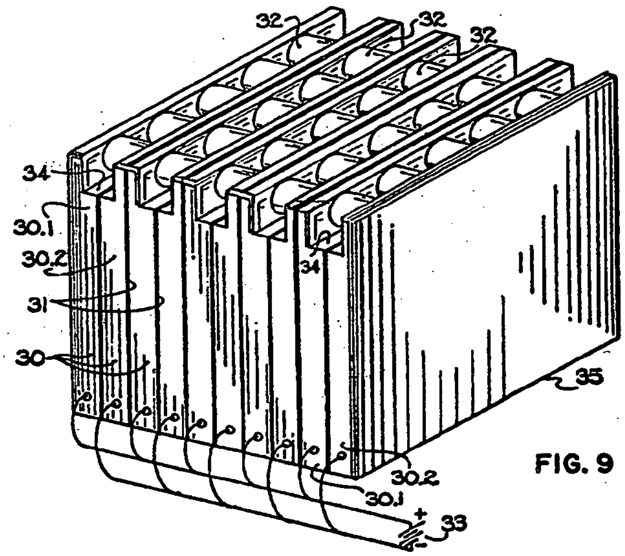

32
32
32
34
30.1
30.2
31
30
34
35
30.2
30.1
+
33
-

FIG. 9

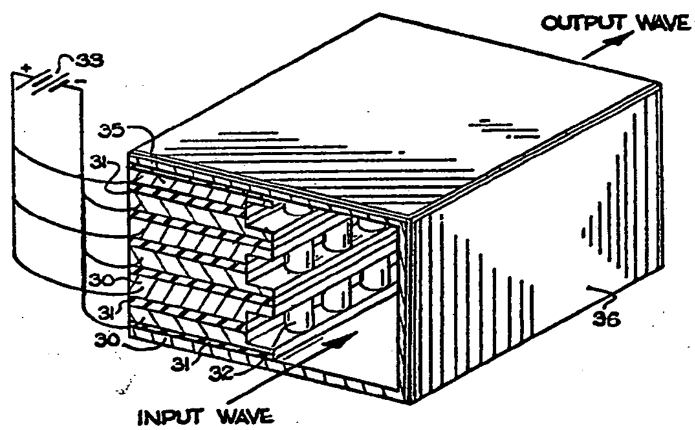

OUTPUT WAVE
+
33
-
35
31
30
31
30
31
32
36
INPUT WAVE

FIG. 10

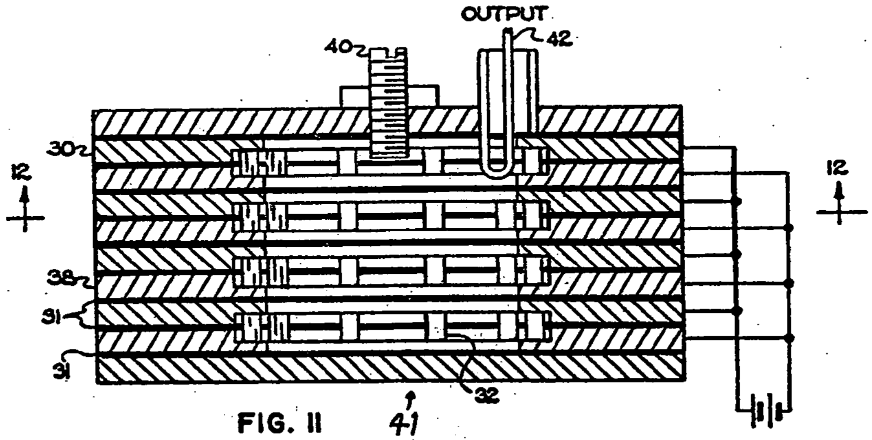


FIG. 11

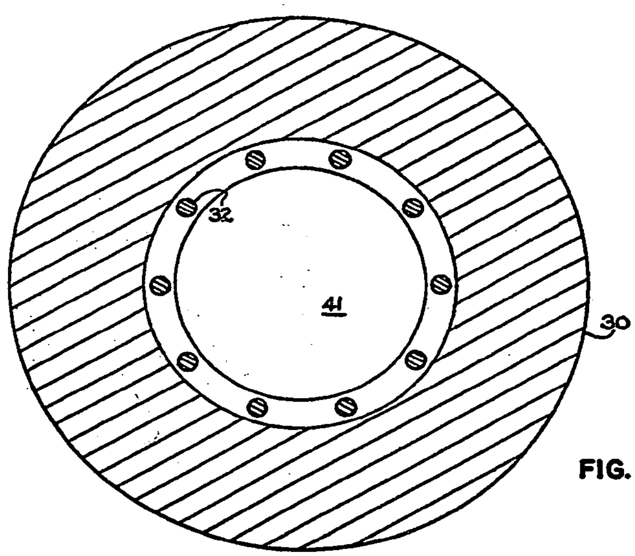


FIG. 12

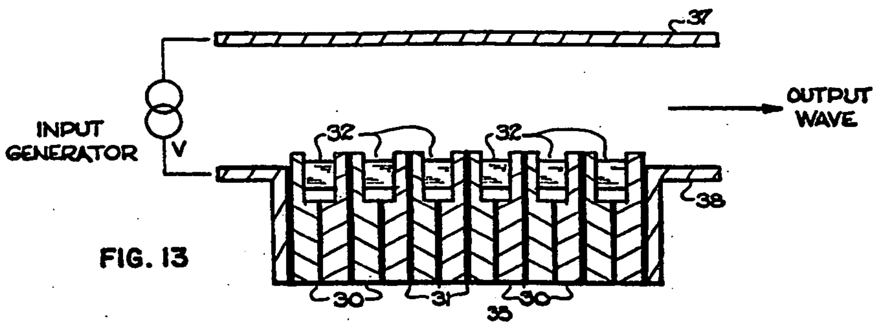


FIG. 13

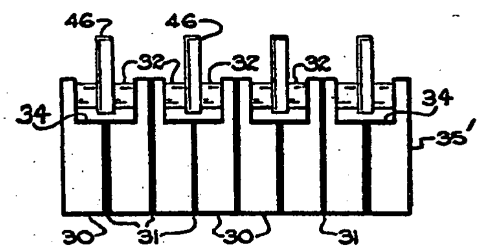


FIG. 14

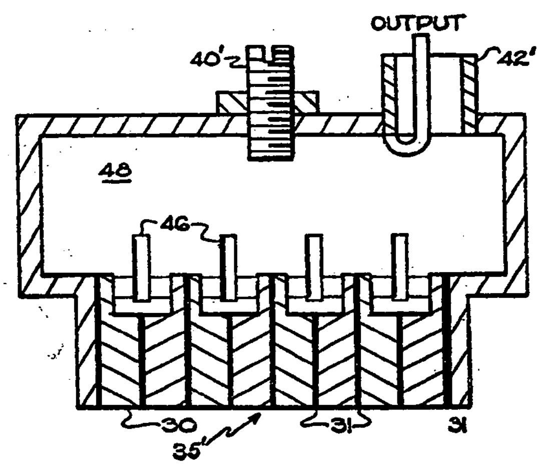


FIG. 15

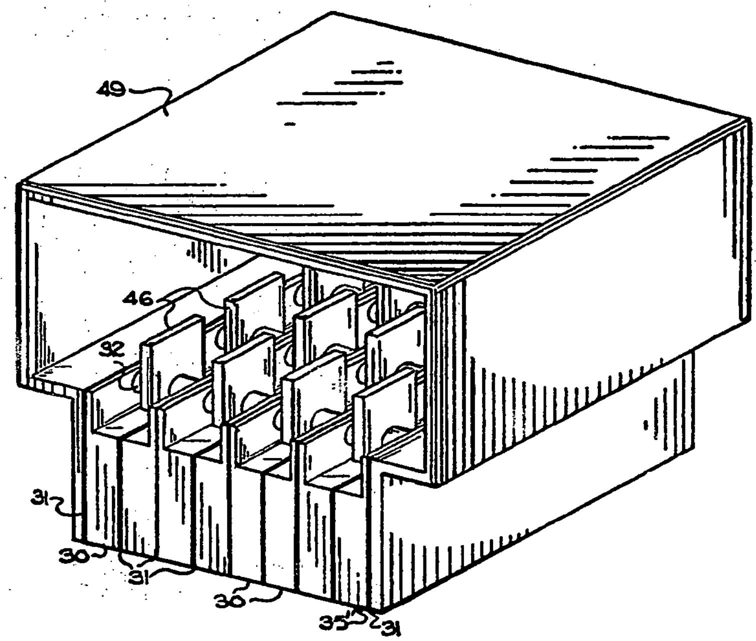


FIG. 16

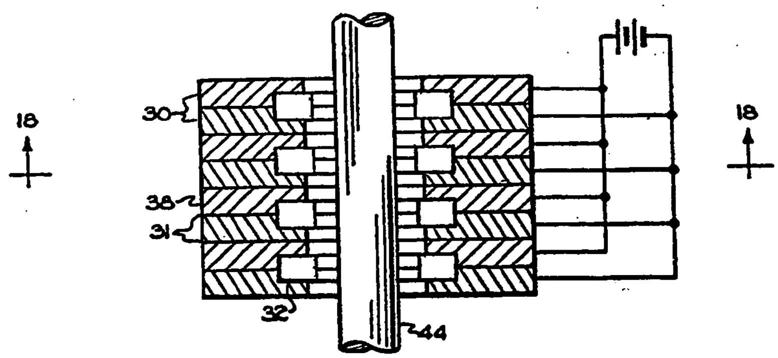


FIG. 17

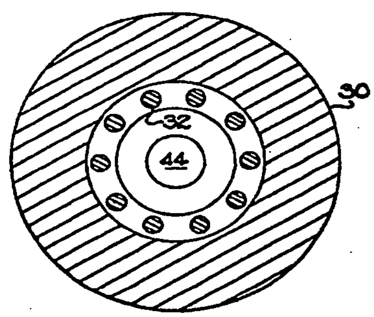


FIG. 18